Solar polarimetry and the need for fast and low-noise detectors

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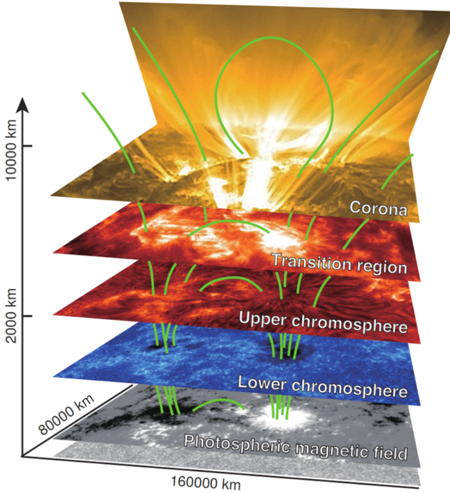


Outline

Today's challenges in solar physics

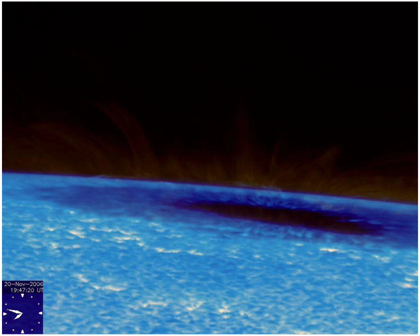
Polarization as magnetic field diagnostics

The difficulties of measuring polarization

State of the art

DEPFET sensors for solar polarimetry?

The solar atmosphere: complex, dynamic and magnetized

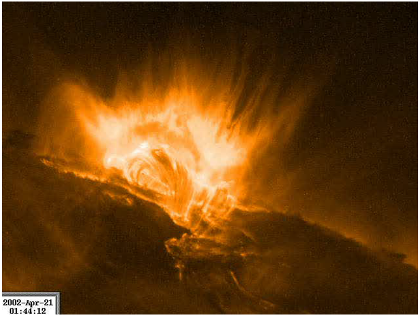


The solar atmosphere is dynamic in all temperature regimes

- from the "cool" photosphere ($\sim$ 5800 K)
- through the chromosphere and transition region
- up to the hot corona ($\sim$ 2 MK)

The dynamics & activity of the solar atmosphere are driven by its *magnetic field*

The solar atmosphere: complex, dynamic and magnetized



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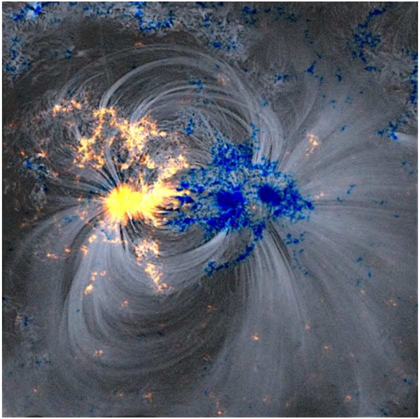

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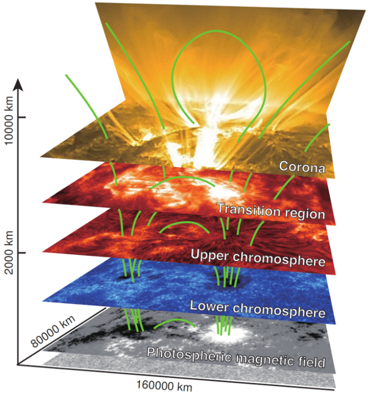
How are the different layers of the solar atmosphere energetically linked?



- Energy loading of the solar plasma due to interaction between turbulent convection and "frozen-in" magnetic field at fundamental scales < 100 km
- Energy transfer and dissipation in higher atmospheric layers (e.g. coronal heating problem)
- Particular focus on the complex and poorly studied *chromosphere*: key interaction region between magnetic fields, waves, flows, radiation

"Hidden" magnetic flux ... or why we have to care about the details!

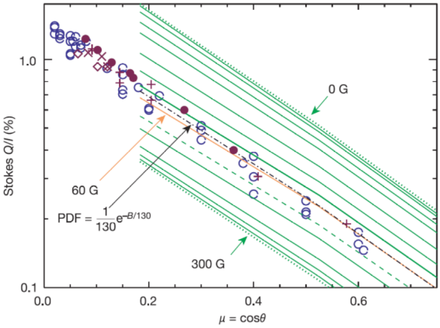
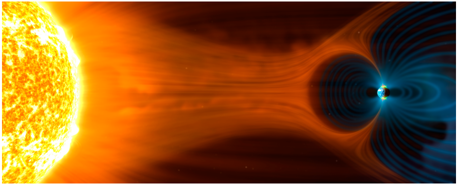
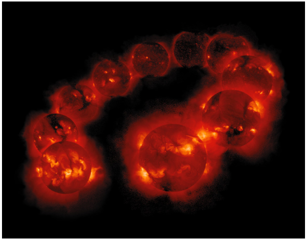


Figure : Tujillo-Bueno et al. 2004, Nature 430, 326

- Relying solely on the Zeeman effect as diagnostic tool, we seem to miss most of the solar magnetic flux!
- Problem: cancelling of Zeeman signals below our spatial resolution limit
- Hanle diagnostics used by Trujillo et al. is not affected by cancellation
- The total "hidden" magnetic flux in the quiet Sun seems to be $\sim$ 1000 times larger than the flux in sunspots!

Sun - Earth connection





How does *solar activity* affect our natural and technical environment?

- Solar wind, space weather
- Solar activity cycle
- Solar irradiance variations

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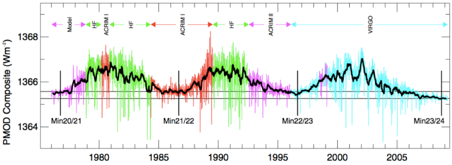

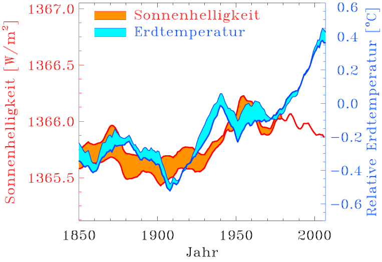

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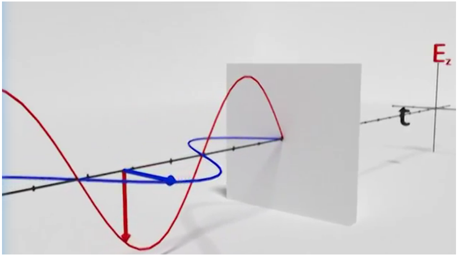
Polarized light as magnetic field diagnostics



- Polarization is a phase property of light
- Magnetic fields influence polarization via
  - interaction with atomic angular momentum (Zeeman effect)
  - or in the context of coherent scattering processes (Hanle effect)
- Polarimetry: encode polarization state into periodic intensity modulation

Polarized light as magnetic field diagnostics

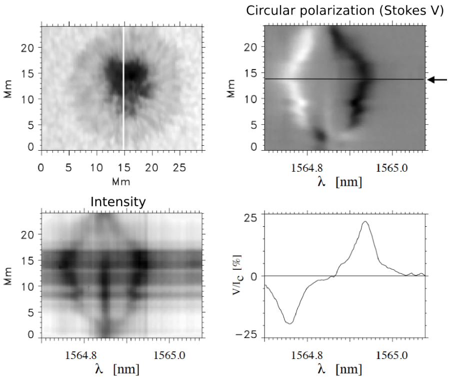


Figure : Schlichenmaier & Collados 2002

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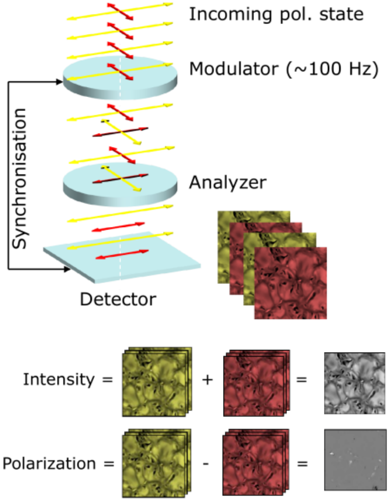

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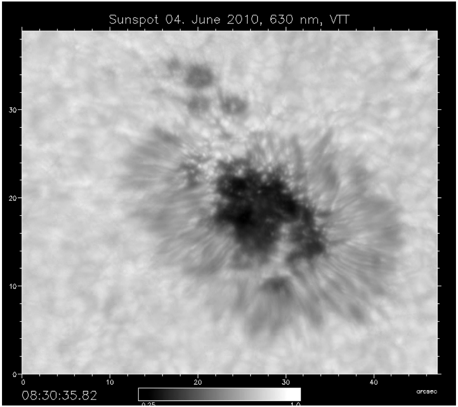
Why do we need fast detectors?



- Polarimetry is extremely sensitive differential photometry
- Polarization measurement can be affected by image instabilities caused by
  - turbulence of the Earth's atmosphere (seeing)
  - instrumental jitter
- Typical seeing time scale: < 10 ms
- Adaptive optics cannot increase polarimetric accuracy

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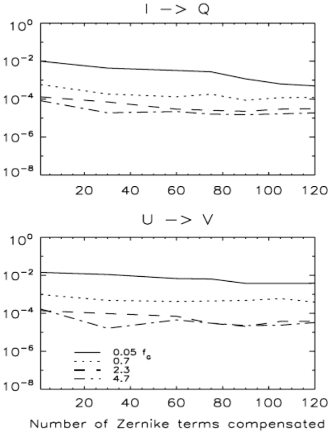

Figure : Nagaraju & Feller, 2012

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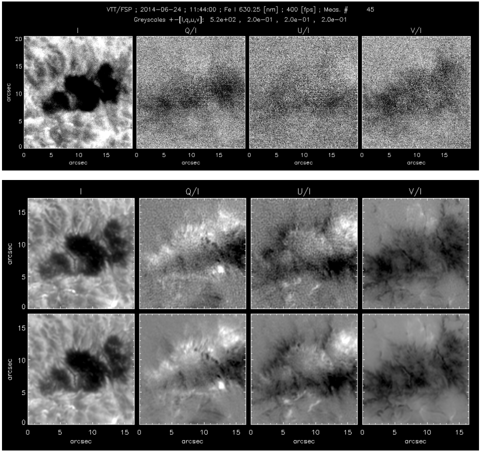

Figure : Fast Solar Polarimeter: single frames, 2s reconstructed images, and 36s average of reconstr. images

Post-facto image restoration is needed

- to reach highest spatial resolution and contrast
- across the whole field of view
- and to increase S/N by averaging w/o losing spatial resolution

Why do we need low-noise and photon-efficient detectors?

The Sun is not bright when you look closely!

- *Seeing* forces us to expose individual frames for less than 10 ms
- *Solar evolution* forces us to reach the required S/N typically within order 10 seconds
- One sensor pixel only samples $\sim$ 1/billionth of the solar surface
- with a spectral bandwidth corresponding to $\sim$ 1/millionth of the total intensity of sunlight
- In strong chromospheric spectral lines the solar flux can drop well below 100 photons per pixel and frame

Zurich IMaging POLarimeter (ZIMPOL)

Figure : Current ZIMPOL-3 camera equipped with an E2V CCD55-30bi with 1280 x 1152 pixels and cylindrical microlenses

- Developed at ETH Zurich since 1990
- On-sensor polarization demodulation
  - by shifting the photo charges between 1 open and 3 covered rows
  - in phase with the polarization modulation
- Very high modulation frequencies up to 40 kHz → seeing completely negligible!

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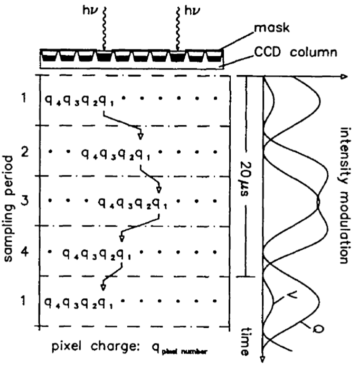

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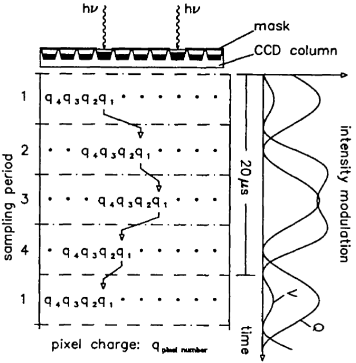


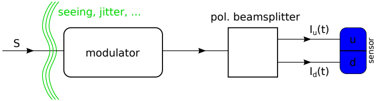
Figure : ZIMPOL on-sensor demodulation principle (Povel 2001)

Disadvantages:

- Effective number of pixels is reduced by factor 4
- Large difference in spatial resolution between x and y dimensions
- Pixel crosstalk (straylight) between open and covered rows
- Slow: current ZIMPOL-3 only runs at ~ 1 fps

ZIMPOL is not suitable for solar imaging polarimetry at highest spatial resolution!

Imaging Magnetograph eXperiment (IMaX)



- Imaging polarimeter onboard the Sunrise balloon borne solar telescope
- Dual-beam technique: strictly simultaneous measurement of 2 polarization states
- Polarimetric sensitivity level of order 0.1%

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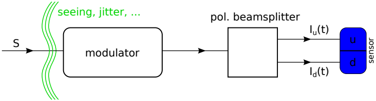

Disadvantages:

- differential effects between the 2 beams
- uncorrected crosstalk between linear and circular polarization
- slow (only 1 complete pol. measurement per s)

Fast Solar Polarimeter

- Collaboration with PNSensor and HLL since 2012, funded by MPG and EC FP7 (SOLARNET)
- Based on
  - pnCCD sensor operated at 400 fps
  - ferro-electric liquid crystals for polarization modulation
- Development in 2 phases:

  2012-2014 Proof of concept with small pnCCD prototype (264x264 pixels^2), single-beam

  2014-2016 Development of full-scale, science-ready version with 1kx1k pnCCD, dual-beam

Fast Solar Polarimeter

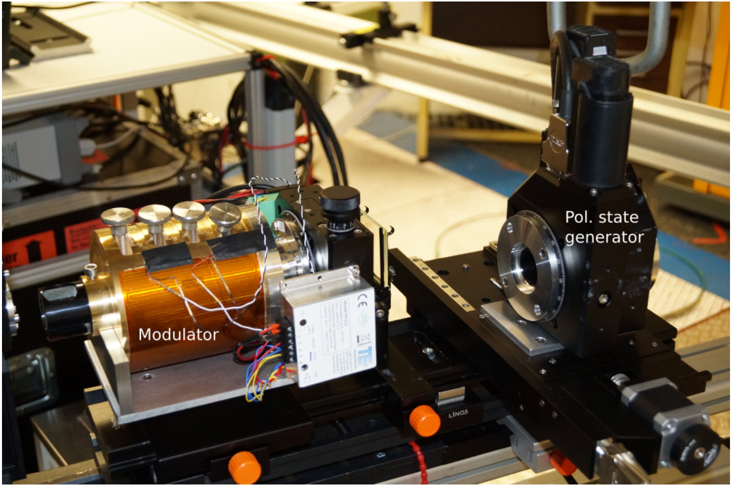

Figure : FSP prototype setup at the German VTT solar observatory, Tenerife

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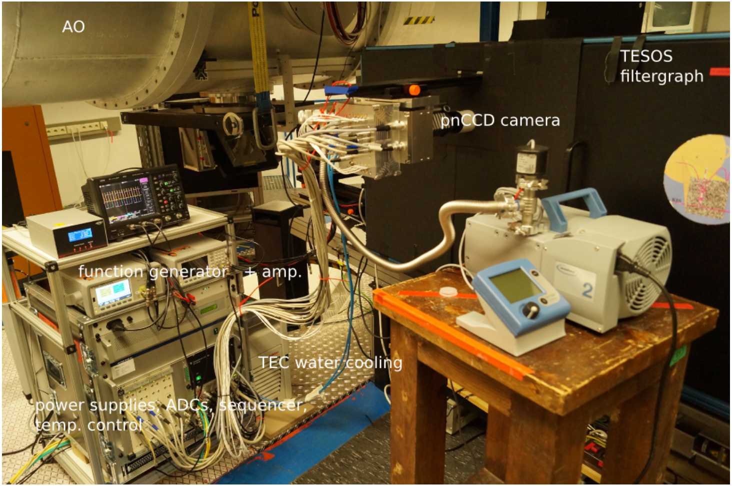

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Fast Solar Polarimeter

Main specifications

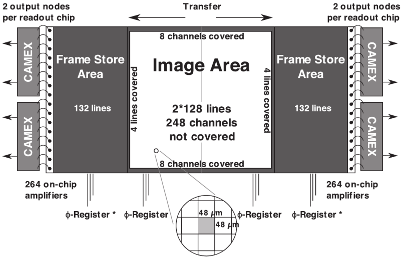
	FSP I	FSP II
Sensor size	264 px x 264 px	1024 px x 1024 px
Max. frame rate	800 fps	400 fps
Pixel pitch	48 μm	36 μm
QE > 90%	500 nm - 870 nm	350 nm - 500 nm
Duty cycle	97%	95%
RMS readout noise	3 - 4 e^-	
Sensitive subst. depth	450 μm	
Readout ASICS x number	CAMEX x 4	VERITAS-1 x 16
Max. data rate	0.78 Gb/s	6.7 Gb/s

Fast Solar Polarimeter

Key concepts

- Fast split frame transfer + numerical transfer correction
- Column-parallel readout
- Multi-correlated double-sampling to reduce noise
- Custom coating to optimize QE
- Thick substrate → no internal fringing

Sensor layout scheme



From Ordavo et al. 2011

DEPFET Infinipix

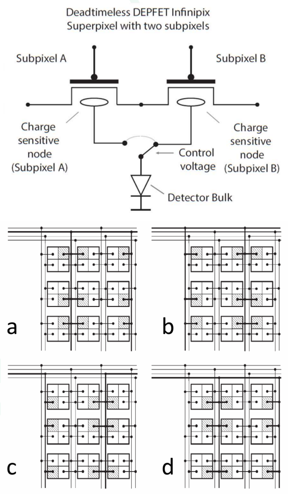


Figure : J. Treis

- ZIMPOL-like, very high-frequency (order 10 kHz or above) on-sensor polarization demodulation
- 100% fill factor, no covered sensor columns
- high frame rate ($\sim$ 100 fps) still allows for high spatio-temporal resolution
- based on superpixel structure with 4 FET cells, i.e. one FET for each modulation state
- Shield electrodes induce periodic photo-charge drifting between the 4 FETs

DEPFET Infinipix

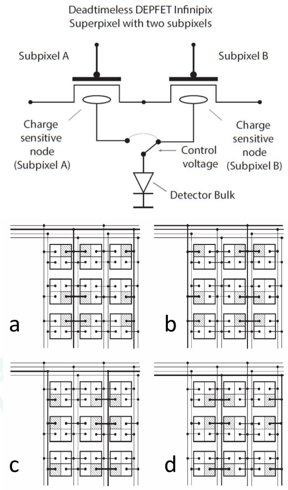


Figure : J. Treis

Next steps

- EC "Horizon 2020" funding available for 2016 - 2019
- First conceptual study in terms of numerical simulations
- Test of a small prototype sensor (32 x 32 superpixels) to assess the true potential for polarimetry

Summary

- Polarimetry is the main diagnostic tool for magnetic fields, which drive all solar activity as well as the still enigmatic energy transfer through the solar atmosphere
- Error sources like seeing and jitter require fast polarization modulation of order 100 Hz
- Rapid solar evolution, short exposure times, and highly selective spatial and spectral sampling leave us in a photon starved regime
- Fast, low-noise and photon efficient detectors, like pnCCDs or sCMOS sensors, are the key technology for today's solar polarimetry
- On-sensor demodulation concepts like DEPFET Infinipix represent a very promising future technology for our field of research